VII. Thermal Architecture

Principles

The thermal architecture of SAFIR is a principal mission challenge, and we have separated discussion of it into this separate section from the previous section on more general architecture because of its importance. The key design principles for a cryogenic telescope in space have been well-demonstrated by the Spitzer Space Telescope. They are:

- Locate the telescope where it can be well-shielded from Sun and Earth
- Require low power dissipation by the instruments
- Design instruments so as to separate warm and cold elements; minimize heat transfer from warm to cold elements.
- Use radiative cooling to the greatest extent practical; minimize active cooling
- Use local active cooling to achieve temperatures below the radiatively-cooled temperature (~15 K)

Underlying these principles is a simple fact: active cooling is very expensive, and complicated. Minimizing the active cooling needed in a mission reduces cost and risk. Implementation of these principles affects almost every aspect of the design of the full flight system to a greater or lesser degree, therefore thermal design drives flight system design. Application of these principles from the beginning of the design process will greatly enhance the success of SAFIR.

In the following sections we describe a point design for the critical sunshade/passive radiator, and active cooling requirements for the telescope mirrors. The orbit and instrument cooling are described elsewhere (Sections VI and VIII). In this section, we assume a conventional design for SAFIR, with a JWST-like structure. The more complicated boom deployed structure described in Section VI can be assumed to offer significant thermal advantages over what we assume here.

Passive Cooling for SAFIR Sunshield

This section describes a point design proof-of-concept for the SAFIR sunshield, and the thermal performance predicted for that sunshield. Performance/design trades are indicated in cases of particular relevance to a detailed design, or where they indicate the need for technology development or for further coupled-model analysis. Results of the thermal—mechanical model analysis indicate that the sunshield performance can meet performance requirements through passive radiative cooling provided that the parasitic loads from wiring are minimized, but that increased lifetime of materials will likely be required to achieve the 10 year mission life. It is also found that active heat lift from portions of the shield mechanical structure can be of benefit in overall mission optimization.

Significant effort has occurred and continues toward the development of a sunshield for JWST. In what follows we indicate how SAFIR expects to incorporate the JWST developments. In some cases the requirements for SAFIR exceed those attainable by the JWST design, so the lessons learned will be noted where they indicate that further development will be necessary or highly beneficial for SAFIR.

Requirements for SAFIR sunshield performance

The SAFIR sunshield serves primarily to reduce the radiant flux from the Sun, Earth, and Moon, which would otherwise scatter into the optical beam, or heat the telescope mirrors above their required operating temperature. The sunshield peformance requirement can thus be expressed as the maximum amount of thermal power radiated from the telescope-facing side of the sunshield. This thermal radiation results in both stray light in the optical beam and heating of the telescope.

Since the telescope will require active cooling to reach the required temperature of ~4 K, the impact of radiative heating of the telescope is easily calculable. While it is a significant factor in overall system design, the telescope heat lift does not yield a science-based requirement on sunshield performance, but simply indicates that a colder shield is better. Straylight considerations yield firmer requirements.

The requirements derived from straylight source suppression depend critically upon the telescope optical design, and are thus difficult to quantify. *By common consensus, a telescope-facing sunshield temperature of approximately 15 K, with an emissivity as small as practical, is expected to provide an acceptable thermal radiation environment for the telescope and instruments.* For purposes of comparative studies, we take 15 K on the coldest shield to be the goal. Recognizing that all shields will exhibit thermal gradients across the surface, we define the "power-equivalent temperature and emissivity" for a shield to be the temperature of a greybody, of the same area and temperature-dependent emissivity as the shield, which would emit the same total power as the shield. This single temperature-emissivity pair then characterizes the entire shield. Further refinement of the requirement could consider the radiation from each area element of the shield surface interacting with the telescope structure and surface, since the outer portions of the shield which will subtend larger solid angle are at lower temperature; but the telescope optical design is not yet mature enough to benefit from this level of detail.

Description of SAFIR sunshield thermal-mechanical model design

In what follows we describe a thermal-mechanical design which satisfies the requirements for a SAFIR thermal shield. The fundamental design is very similar to that of JWST; five layers of highly reflective material in a V-groove configuration, each layer successively colder from sun to telescope side, and each layer rejecting to space a large fraction of the heat it receives from the next-warmer shield. The inner section of each layer is fixed in position, while the outer segments of the shields are membranes, deployed via booms attached at the 300 K spacecraft, and tensioned using cantilevered spreaders. The deployed shields are similar to those of JWST; flexible and with very limited lateral thermal conductance. For this study, the shields are assumed thin enough that there is no temperature difference between the warm-facing and cold-facing sides of a single shield at any point, although each shield will have temperature variation across the surface.

The deployment mechanism is essentially the same as that developed for JWST, scaled to the larger area of SAFIR. The deployment booms have optical properties the same as those of the sun-facing shield to which they are adjacent. The effect of occlusion of the sun-facing shield by the spacecraft bus and solar panels is assumed negligible, as the fractional area is only a few percent of the sunshield footprint. For definiteness, the sun-facing shield footprint taken to be 20 m x 40 m, deployed. The configuration analyzed has an angle of 5 degrees between shields, in a bookfold configuration; i.e., the stack has only one vertex, that being along the short axis, with a separation of 20 cm between successive shields at the vertex. Figure VII-1 shows the design of the JWST spacecraft and of the configuration chosen for the thermal-mechanical model whose performance is reported here. As noted above, for the purposes of this section, in order to most clearly benefit from JWST design heritage, we assume the more conservative JWST-like design described in Section VI, rather than the boom deployed version.

A mechanical strut structure extending from the spacecraft bus to the base of the telescope mounting attachment provides thermal isolation and mechanical attachment between the spacecraft and telescope, while carrying instrumentation, active cooling lines, and other infrastructure. This structure has the form of a hexapod terminated in rings on each end; the diameter of the structure is 2 m. For thermal modeling, the central 2 m x 2 m section of the shield assembly, occupied by the support structure, is fixed in position and is allowed to have much larger thermal conductance than the deployed membrane shields. Figure VII-2 shows the hexapod-and-ring support structure with fixed panels attached; the membrane sections are deployed outward from the fixed panels.

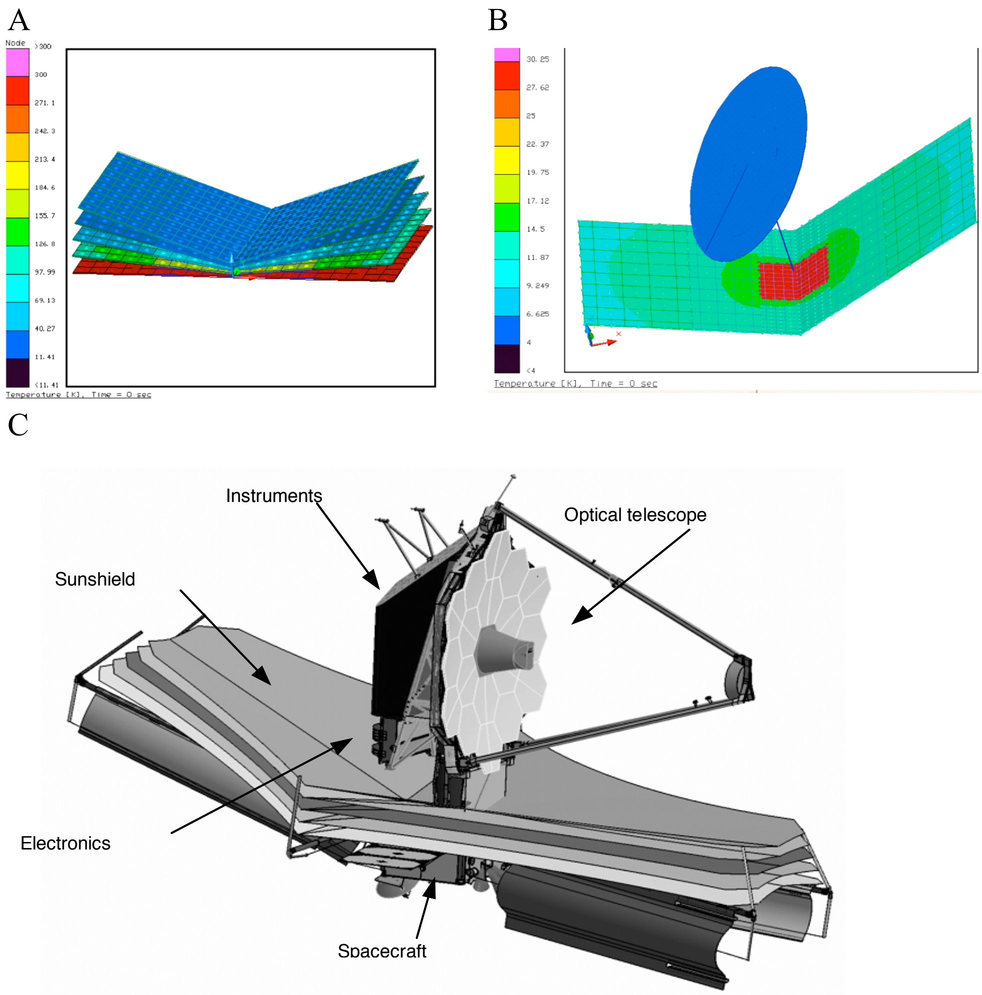


Figure VII-1: Configuration of SAFIR sunshield panels for thermal analysis, and JWST current design. A: Five-shield stack in bookfold configuration: 5 degrees relative angle between adjacent shields, 20 cm spacing of vertices. B: coldest shield with telescope representative optical model. C: JWST spacecraft design, showing similarity with SAFIR sunshield thermal model. For SAFIR, the telescope mounting tower could differ significantly from that shown for JWST, perhaps being an articulated boom.

Following launch, the sunshield carry-through structure is required only to apply the loads associated with observatory operation: L2 orbit insertion, repointing, and stationkeeping. To reduce the thermal conductance of the carry-through structure, we have assumed that launch loads associated with the telescope and instruments will be not be applied through the sunshield structure, but via some detachable alternative path. Designing the structure to carry only the operational loads allows optimal thermal decoupling of the warm spacecraft from the cold telescope, and minimizes thermal parasitics between the sunshield layers. This is one example of how consideration of thermal issues at an early stage of design can achieve much better thermal performance than otherwise possible.

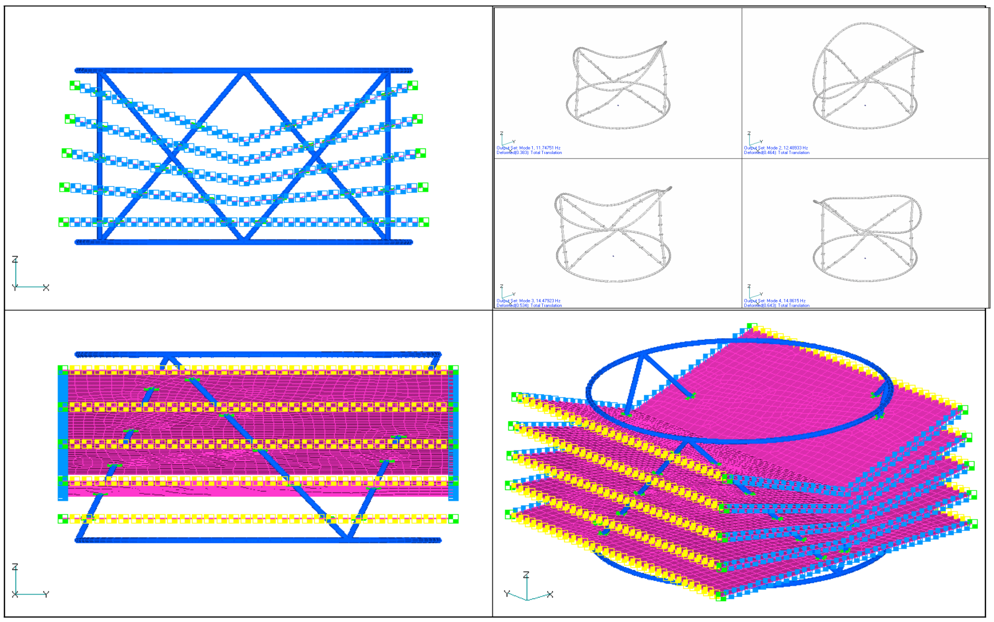


Figure VII-2: Hexapod support structure for carrythrough of operational loads, showing inner (non-deployed) segments of sunshields. Lower ring attaches to spacecraft, upper ring attaches to telescope support, inner segments of sunshields attach at intermediate connectors of struts. Modal analysis of first four modes of structure shows all modes are >10 Hz. Inner panel footprint is 2 m x 2 m.

Using operational loads calculated from the Team-X study (see Appendix A), and assuming lightweight rigid sunshield panels for the inner 2x2 m of the sunshield structure, the strut dimensions and resulting thermal conductance for the carry-through structure have been calculated. It is found that standard composite materials (GFRP, CFRP) provide sufficient strength, rigidity, and thermal isolation for a workable design. Essentially, this shows that the sunshield thermal performance is dominated by radiative transfer between shields, and not by heat conducted along the structure. Since commonly employed materials provide adequate thermal performance, it is concluded that a sunshield structure for SAFIR can be constructed without further development of structural materials**.**

The optical properties of the shields are of paramount importance to the thermal performance. The sun-facing surface of the warmest shield is coated with silver-teflon, which provides the best available ratio of solar absorbtivity and thermal emittance. Solar absorbtivity of 0.08 BOL, 0.23 EOL (5 years), with thermal emissivity of 0.88 unchanged, is typical. The degradation in solar reflectivity results in overall sunshield performance degradation of order 2-3 K at the coldest shield in 5 years; the change is roughly linear with time. Although the degradation could be partially overcome with increased active heat lift from the coldest shield, at least for conductive loads, the changed thermal environment at the outer shields is not easily mitigated. Thus the performance of the sun-facing shield over mission life is identified as an area in need of improvement.

Low emittance (high reflectivity) on all other surfaces, with the possible exception of the telescope-facing coldest shield, is optimal for minimizing radiative transfer. Thermal modeling assumed emittance of all sections of the shields as given by the Hagen-Rubens relation for emittance as a function of temperature, with emittance consistent with reported values. Again the degradation over time and exposure to the L2 environment will impact sunshield performance. JWST should provide some measure of the expected performance, but the degradation of deployed sunshield thermal-radiative characteristics must also be considered an area in need of better understanding.

The JWST sunshield development will provide considerable advancement in materials and coatings required to enable cryogenic observatories to last more than 10 years in space. In addition to the deployment models, non-linear analyses of the sunshields shape and dynamics, the JWST project has modified several facilities around the country to enable qualification of the sunshield to the unique low energy plasma and micrometeoroid environment of L2. These developments will be tracked by the SAFIR team and incorporated into the design. We expect to incorporate significant heritage from the JWST effort into the design, testing, and validation of the SAFIR sunshield.

Sunshield thermal performance predictions

Results for the temperatures of the sunshield layers under various conditions are shown in Figure VII-3. The temperatures and emissivities are the "power-equivalent" values, as described above. Temperature profiles for the coldest, telescope-facing shield ("Shield 5") is shown for each case. In all cases the thermal conductance of the deployed membrane portion of each shield is zero, while the conductance of the fixed inner segment is determined by the materials chosen. Results for both an aluminum-faced honeycomb panel and a zero-conductance panel are shown for comparison.

The effect of a high (0.8) emissivity on the telescope-facing side of Shield 5 is also shown, for comparison with the low-emissivity (~0.013) case. High emissivity on the telescope-facing surface results in a decrease in temperature, but an increase in the total radiated power toward the telescope, along with a shift in the wavelength of that power closer to the center wavelengths of interest.

Conclusions from thermal performance predictions of SAFIR sunshield model

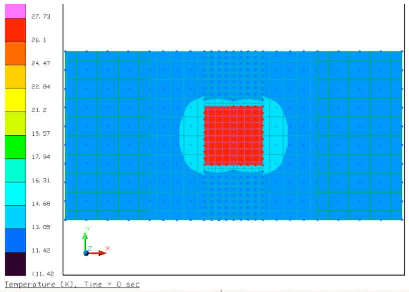
The primary conclusion to be drawn from the thermal-mechanical model results is that radiative cooling alone is probably sufficient to achieve the thermal performance required of a sunshield for SAFIR, provided wiring loads are minimized. In more detail:

1. Mechanical structures fabricated of materials commonly utilized for space applications have strength-to-thermal conductance ratios compatible with the requirements.

2. The optical properties of deployable sunshield materials, for example aluminized Kapton, provide adequate decoupling of adjacent shields and rejection of radiation to space to achieve an effective 15 K low-emissivity (<0.015) telescope-facing coldest shield.

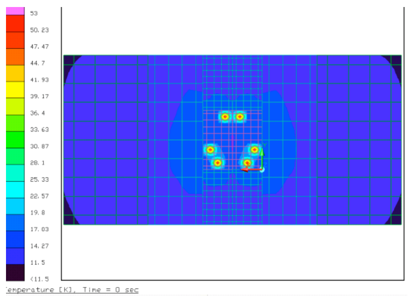
3. Lateral thermal conductance in the deployed sunshields is not required to meet the performance. The same is true for distributed heat lift from the shield surfaces. Models indicate that non-vanishing conductance or distributed heat lift would be beneficial, but not necessary.

4. Lateral conductance in the fixed segments of the sunshields, i.e. in the central 2 m x 2 m area, is not necessary to meet the temperature requirement, but is beneficial in extracting heat conducted along the support structure, and rejecting it to space. With modest conductance of the inner shield segments, and the shields coupled to the structure at the points of penetration, the coldest shield and support structure meet the temperature requirement with margin.



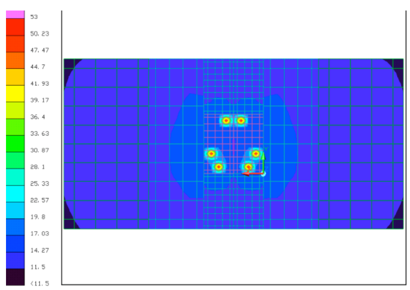
Case A	T_shield [K]	E_shield
Shield 1	279	0.056
Shield 2	145	0.041
Shield 3	69.1	0.029
Shield 4	28.8	0.019
Shield 5	14.0	0.013

A. Fixed inner segment is 0.020 cm aluminum (two face sheets on a honeycomb core)



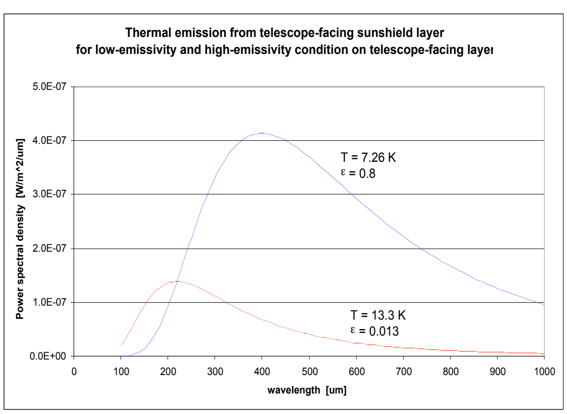
Case B	T_shield [K]	E_shield
Shield 1	279	0.056
Shield 2	145	0.041
Shield 3	69.1	0.029
Shield 4	28.4	0.018
Shield 5	13.3	0.013

B. Fixed inner segment has zero thermal conductance. Average shield temperature is lower because struts to not thermalize at shields. The struts are visible as hot spots at the points at which they penetrate the shield.



Case C	T_shield [K]	E_shield
Shield 1	279	0.056
Shield 2	145	0.041
Shield 3	69.1	0.029
Shield 4	28.4	0.018
Shield 5	**7.3**	**0.80**

C. Fixed inner segment has zero thermal conductance. Telescope-facing side of Shield 5 has emissivity fixed at 0.80. Average shield temperature is lower compared to b) because the average emissivity is increased, but the power radiated toward the telescope is increased due to zodiacal input, and is shifted to longer wavelength.



D. Power spectral density radiated from the telescope-facing side of Shield 5, for cases B and C. Red curve is E=0.013 (case B), blue curve is E=0.80 (case C), for telescope facing side of Shield 5. The data are calculated for one particular configuration of sunshield. The emissivity of the warm-facing side of Shield 5 is temperature-dependent, but nearly equal in both cases. The power radiated toward the telescope is larger for case C due to higher emissivity and increased absorption of zodiacal background. At this temperature the power absorbed from the zodiacal background is a significant contribution to the Shield 5 temperature.

Figure VII-3: Temperatures for the SAFIR sunshield layers for various configurations.

The JWST sunshield design will provide extensive heritage in materials, deployment, and performance validation, albeit to higher temperature than SAFIR. By considering the thermal performance as part of the overall mechanical design of the entire system, many of the limitations of the JWST design can be overcome. In particular, the sunshield core area design must provide for interception of heat conducted along wiring from the warm (300 K) spacecraft bus, along the sunshield structure, to the telescope and instrument package. Designing the instruments to minimize wiring loads will benefit the overall performance. Thermalization of wiring bundles at each shield may allow the conducted heat to be radiated to space without serious degradation in the shield performance. If the conducted loads prove too large, thermalizing the wiring harness at the precooling temperatures of the active coolers (addressed later) is an attractive option; this is likely to be technically easier than active cooling of the shields themselves.

As indicated above, the requirement on temperature and emissivity for the coldest shield is not yet mature. Should the requirement become more stringent as optical analysis of the telescope matures, it is possible to extract heat from the central section of the coldest one or two shields with an active cooler, which would result in an overall reduction in the coldest shield temperature. The two coldest shields central sections typically have temperatures of ~40—45 K and 19—22 K, depending upon other conditions; these temperatures are well-matched for performance improvement with the two precooling temperatures of the ACTDP coolers; 35 K and 15 K. More details on the active cooling are available in another section.

It is worth noting that the straylight scattered into the beam from this open-planar sunshield design is significantly less than for a more tightly-shrouded telescope. Since the shield surface is itself a source of straylight, the smaller solid angle subtended by the open-planar sunshield results in less scattering into the optical beam. The open design of sunshield is also more compatible with an off-axis telescope configuration, which is itself superior as regards straylight.

Active Cooling for the SAFIR Telescope and Instruments

In this section we consider the requirements on active cooling of the SAFIR telescope, both for heat lift from the mirror and heat rejection from the active coolers, and describe multiple options for achieving the 4 K telescope temperature.

Thermal emission from the telescope optical surfaces is a source of photon noise for the instruments; it must be small enough that it does not compromise instrument sensitivity. The benefit of decreased telescope temperature is seen in Figure VII-4, which shows the increase in telescope size required to maintain a fixed signal-to-noise ratio over the wavelengths of interest, as the telescope temperature increases. The same S/N can be achieved at higher temperature only by increasing the collecting area, which very quickly becomes prohibitive (note that the vertical axis in Figure VII-4 is telescope diameter, not area). For the faint targets and long wavelengths of interest for a 10-m diameter SAFIR, there is clear benefit in cooling the telescope to ~4 K, but limited gain in cooling the telescope further. This is then the selected requirement on the temperature of all telescope elements, and of any structural components in the beam. *Active cooling of the telescope is needed in order to reach 4 K, as this is below the temperature attainable through radiative cooling.*

Observing techniques which make use of multiple sections of the telescope surface impose limits on the variation in temperature across the aperture. Uniformity in telescope temperature to 0.1 K across the 10 m primary aperture is the accepted requirement. Similar requirements will exist for subsequent telescope elements, but will be more difficult to meet on the primary.

Instruments for the far-IR will require cooling of the surroundings and internal optics, to temperatures of 4 K and below. While these requirements are not yet well-defined, it is assumed that whatever techniques are employed to cool the mirror will also be applicable to the instruments. Cooling below 4 K, while necessary for instrument performance, is not addressed as part of this section aside from recognizing that whatever system provides cooling to the telescope can also provide precooling for the instruments and surroundings.

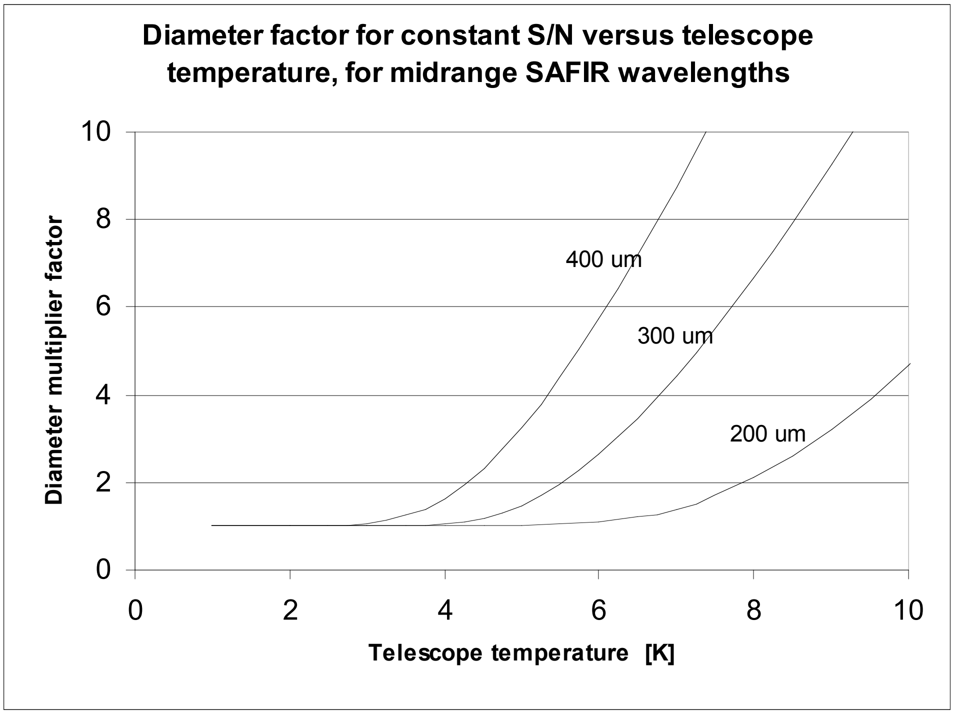


Figure VII-4: Diameter factor for constant S/N versus SAFIR telescope temperature, for wavelengths of interest to SAFIR. Calculation assumes telescope emissivity of 0.05, and zodiacal background from a simple model of Lockman hole values [following E. L. Wright, IAU Symposium on Extragalactic IR Background, 2000]

Prior telescopes which have required cooling to 4 K and below (Spitzer, COBE, ISO) have all been less than 1 m in diameter, and have been cooled by expendable cryogens surrounding or cooling the telescope directly. This approach is physically impractical for a 10 m SAFIR, and unacceptable for its life-limiting use of cryogens. SAFIR will likely be the first telescope to utilize active mechanical coolers to reach the temperature required for far-IR instruments. Development of mechanical cryocoolers capable of providing 4 K at a telescope which is remote from the high-power components of the cooler is an enabling technology for SAFIR. The Advanced Cryocooler Technology Development Program (ACTDP), funded by NASA’s Navigator program and administered through JPL, has produced promising results along the path to such coolers, but more work, in particular for lower temperature and deployment of remote cold heads, is required. In this area JWST, which has recently decided to utilize a remote cold-head mechanical cooler to cool its mid-infrared instrument to below 7 K, is expected to provide significant experience to SAFIR.

The 10 m diameter SAFIR telescope will clearly require deployment following launch. Several deployment options are available for a 10 m diameter primary mirror, as is discussed in Section VI on Architecture and Implementation, but irregardless of which method is selected, the individual segments are likely to be substantially thermal isolated from each other to allow for deployment, surface figuring, and alignment. Each segment will thus require attachment to a source of cooling. This would certainly be the case for the multifolded and rotationally stacked deployment schemes, and probably also for a JWST-like chord-fold. If a DART-type multi-membrane design is employed with metallic membranes, thermal conductance of the membrane will be large enough that a small number of heat exchange points on the frames will suffice. For membranes with very low thermal conductance, a design with high-emissivity coupling between the reflector back surface and a conductive layer in proximity will provide cooling, again with multiple heat exchange points to the conductive layer.

Thermal radiation from the sunshield to the telescope is the largest source of heat into the primary; the thermal load is significantly larger on the portion of the telescope closest the sunshield. The current baseline design of the SAFIR telescope calls for articulation of the primary relative to the sunshield, which will result in significant variation in the thermal loading across the primary mirror with repointing. Development and demonstration of a system for extracting heat from multiple points, at well-controlled temperature and under varying thermal loads, is thus a critical technology need for SAFIR. The number of heat lift points will likely exceed 10 (at least 7 for the primary, one for each of two additional monolithic mirrors, and one for the instrument package), and could easily exceed 20 if more segments and structure must be cooled. Most cooling locations will require the some sort of deployment of a cold head, so *development of deployable heat exchangers must be an integral part of the development effort***.**

As noted, active cooling of a telescope has not previously been required; the JWST telescope will reach ~35—45 K through passive radiation, and Spitzer attains <5 K via stored cryogens which are not available for SAFIR. COBE and ISO cooled to ~2 K by surrounding the mirror with a cryogen dewar; neither the cryogen nor the structure are workable options for SAFIR. Active cooling of a telescope to 4 K will thus require new techniques for reaching 4 K, deploying the cooling sources to multiple points of the telescope, and maintaining both the temperature and uniformity under time-varying thermal loads. In what follows we describe a cooling system to meet these requirements, and the developments needed to develop and demonstrate this system.

Forced flow cooling loop for telescope

The system under consideration is a forced flow loop of cryogenic helium at 4 K proceeding in series through several heat exchangers. Several design options are available: the flow can be two-phase liquid plus vapor on the saturation curve, single-phase vapor, or single-phase liquid maintained above the saturation pressure. The first option is selected for primary consideration, since it provides some advantages for thermal control; but all three options will be discussed. More than one circulation loop with multiple heat exchangers can coexist as needed, but for simplicity we will discus only one loop, as is shown schematically in Figure VII-5, for a segmented primary and for a radiatively-coupled membrane.

1. Two-phase saturated fluid loop: The helium flow will be driven by a compressor similar or identical to the ACTDP J-T compressors, residing on the warm spacecraft bus. The flow pattern is illustrated in Figure VII-5. The input flow can be separate from the ACTDP cooler, or it can be the flow through an ACTDP-type cooler operating in the 2-phase regime, in which case this cold end would be an extension of the ACTDP single cold finger. In either case, the output of the J-T is saturated liquid + vapor ^{4}He at 4 K. This flow proceeds by pressure and viscous drag through the piping to the heat exchangers, where heat is absorbed at constant temperature by evaporation of liquid. Since all evaporators (heat exchangers) are at essentially the same pressure, the temperature is the same at all points, ensuring temperature uniformity across the multiple segments of the aperture. Since the quantity of heat absorbed at any evaporator is exactly the amount required to cool the attached segment to 4 K (since the liquid and vapor are on the saturation curve), differing thermal loads on different segments have no effect on the local temperature. This design provides automatic load balancing, as is needed for example when repointing moves one segment closer to the sunshield. By contrast, in a single-phase flow loop the fluid increases in temperature as heat is absorbed, so some means of ensuring constant temperature with load changes would be required.

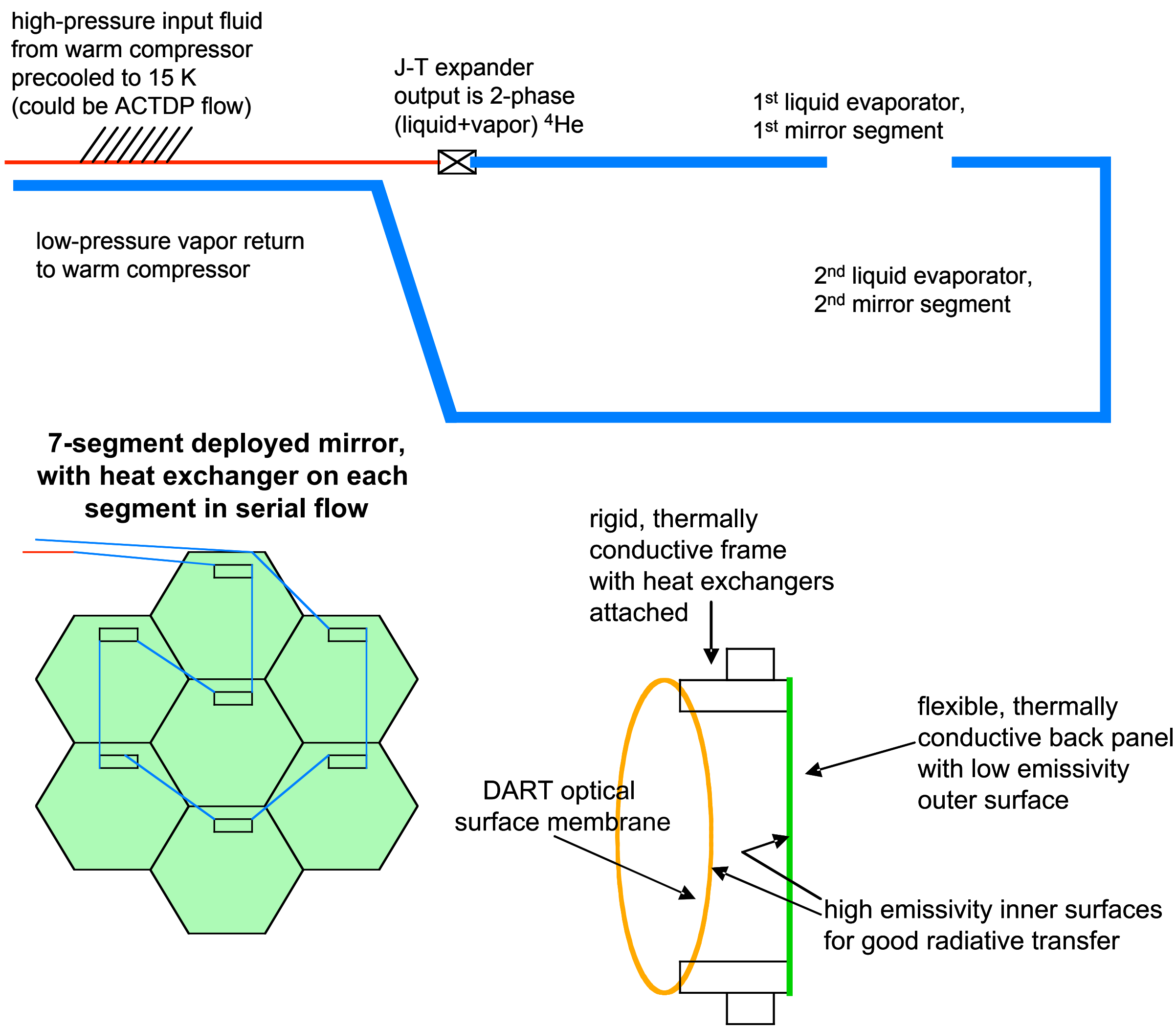


Figure VI-5: (top) Schematic diagram of forced flow cooling loop for SAFIR telescope cooling. (bottom left). Forced flow loop with precooling, J-T expansion, and liquid evaporators; also shown is cooling loop attached to 7-segment primary mirror. (bottom right) Cooling loop on a DART-like structure with radiative coupling of membrane to cooled surface.

The 2-phase fluid loop requires that pressure in the return line be slightly less than 1 bar, to achieve 4 K in the saturated liquid. This pressure is lower than is currently used in the ACTDP J-T compressors, for which the recovery pressure is ~2—4 bar. Other compressors can function at this recovery pressure, but some development of the compressor system is likely to be necessary to demonstrate a flight-qualified system.

2. Single-phase, supercritical vapor flow loop: Figure VII-5 also illustrates this option, with the differences being that the output flow is supercritical ^{3}He rather than two-phase ^{4}He, and that the heat exchangers are transferring heat to vapor, not acting as liquid evaporators. This is probably the cooling technology closest to maturity, with only the change to ^{3}He and some changes to the heat exchangers being required. The most significant difference is that the temperature is no longer constant at all the heat exchangers; instead it increases with heat absorbed, which could change with repointing and other operational changes. Multiple flow loops, with flow adjusted to maintain temperature, could solve the problem at some cost in system complexity.

3. Single-phase, supersaturated liquid flow loop: Again Figure VII-5 illustrates the essentials, with some changes. In this case the J-T restriction would become a condenser restriction, with precooling to ~4 K by the ACTDP single-point cold end resulting in 100% liquid ^{4}He outflow. Pressure in the output line is maintained above saturation pressure, so the heat exchangers and return line can be smaller than in the other cases because the fluid is more dense. The problem of temperature increasing with heat absorption is greater for this case because the heat capacity of the liquid is less than that of the vapor, but detailed system design would indicate which approach is preferred.

The two-phase forced flow loop design is based upon JPL's experience with the Planck Sorption Cooler, which employs two separate heat exchangers in a series loop, with saturated hydrogen as the working fluid. While the temperature and fluid differ, the engineering considerations of zero-G fluid flow and heat exchange are similar; however, the engineering challenges are not to be minimized. Whether the automatic load-balancing offered by the 2-phase system outweighs the simplicity of a single-phase system will be determined by the detailed design. In sum, any of these flow loop approaches can yield the temperature and uniformity required for SAFIR, but all require some development in the 4 K cooling system and in heat exchangers compatible with the telescope, deployment, and zero-gravity operation.

Deployment of forced fluid loop for telescope cooling

Deployment of the fluid loop occurs in the same way as that for the wiring for mirror segment adjusters, micropositioners, and instrument cabling. For example in the case of the rotationally stacked deployment, the two flow pipes (input and output, which are likely to be coaxial) would be bundled with the cabling, and would experience an uncoiling of 300 K at several locations, as the mirrors pivot at vertices. The pipes can be flexible enough that this will not require development beyond current capabilities. As noted above, JWST has recently decided to employ an ACTDP-type cooler in the Mid-InfraRed Instrument (MIRI); while this cooler will provide cooling via a single deployed cold head, to an instrument rather than a telescope, still the experience gained will be of considerable benefit to SAFIR.

Thermal modeling has indicated that 1 m diameter mirror segments of Be, SiC, and CVD-encapsulated Si foam and SiC foam (see Sections VI and XV) all will likely possess adequate thermal conductance that only a single heat exchanger on each segment will be required for temperature uniformity. For larger mirror segments, or segments with poorer thermal conductivity, multiple heat exchangers per segment can be used to reduce gradients.

Consideration of alternative cooling distribution techniques

Several alternative methods for removal of heat from the telescope elements have been considered, but do not appear to be preferable; they are discussed below.

1. Heat pipes: Flexible, capillary-pumped heat pipes could in principle connect from a single ACTDP cold finger to all other points requiring cooling, and do so at a nearly constant temperature. However, heat pipes operating at 4 K are far from a mature technology, they are not as flexible or lightweight as the piping for a forced flow loop, and the material properties of liquid helium are highly unfavorable to the fundamentals of heat pipe operation.

2. Mechanical conductive straps connecting to a single cold finger, while mechanically simple, would be significantly more massive than heat pipes and possibly no more flexible when the same performance was achieved.

3. ADRs (Adiabatic Demagnetization Refrigerators) at each point of heat extraction: We make the assumption that intermittent operation of the cooling system, and thus of the observatory, is unacceptable; this requires that the magnetic refrigerator be of the Continuous-ADR (CADR) variety, with an isothermal coldest stage. CADRs function by absorbing heat at low temperature and rejecting it at higher temperature; the heat from each ADR must still be removed. Two options for heat extraction from the ADRs can then be distinguished. If the heat extraction from the individual ADRs is via a flow loop or conductive links or heat pipes, the result is an increase in the heat rejection temperature at a large cost in system complexity, while retaining conductive links or fluid at relatively high temperature compared with direct cooling. Overall this seems a much more difficult method of achieving cooling than is required or prudent. Alternatively, if the ADR accumulated heat is to be radiated to space, a secondary radiator system shielded from the telescope and from the sunshield is required in order to achieve reasonable duty cycle, and the ADR design quickly approaches the limits of superconducting materials. Details of the design requirements depend on heat loads and operating conditions, and quickly become rather involved, but upon some consideration this does not appear to be a viable approach to cooling the SAFIR mirror.

Spacecraft heat rejection

The mechanical coolers for SAFIR will demand a significant fraction, probably greater than 50%, of the electrical power, and must reject the waste heat produced by the multiple cryocooler compressors. This is not a trivial requirement when considering that the overall observatory configuration presents very little clear view to space for the cooler heat rejection system radiators. Rejection of the 800-1000 watts of cooler compressor and electronics power dissipation presents a unique challenge to the thermal design of the spacecraft bus. In this area in particular, the experience gained with JWST will be immediately applicable to SAFIR. Shown in Figure VII-6 is a notional heat rejection system being studied for the JWST spacecraft bus. Two to three of these systems would suffice for SAFIR. Since it is ideal for the cooler compressors to be located central to the bus a series of constant conductance heat pipes transport the cooler heat to a series of variable conductance heat pipes. The variable conductance heat pipes incorporate a flexible bellow sections that allows the pipes to transport heat to a deployable radiator system. The variable conductance heat pipes are self-regulating and will eliminate the need for any supplemental heater power when the coolers are not operating. An alternative, currently being studied for JWST, to the variable conductance heat pipes include loop heat pipes and capillary pumped loops, also incorporating flexible sections.

Thermal Verification

Like JWST, SAFIR will simply be too large to thermal balance test in its fully deployed flight configuration. Lacking this final definitive test that is the keystone for most space mission's thermal verification, SAFIR will most likely follow the JWST paradigm for thermal verification, which relies on thermal modeling, margin control and quality assurance, and assembly and subassembly level testing to verify the thermal models in a piecemeal fashion. In addition to developing the necessary facilities, e.g. the JSC cryotest facility, the order and types of test planned for JWST can be duplicated for SAFIR. A series of validation and verification tests similarly to what is planned for JWST is described below.

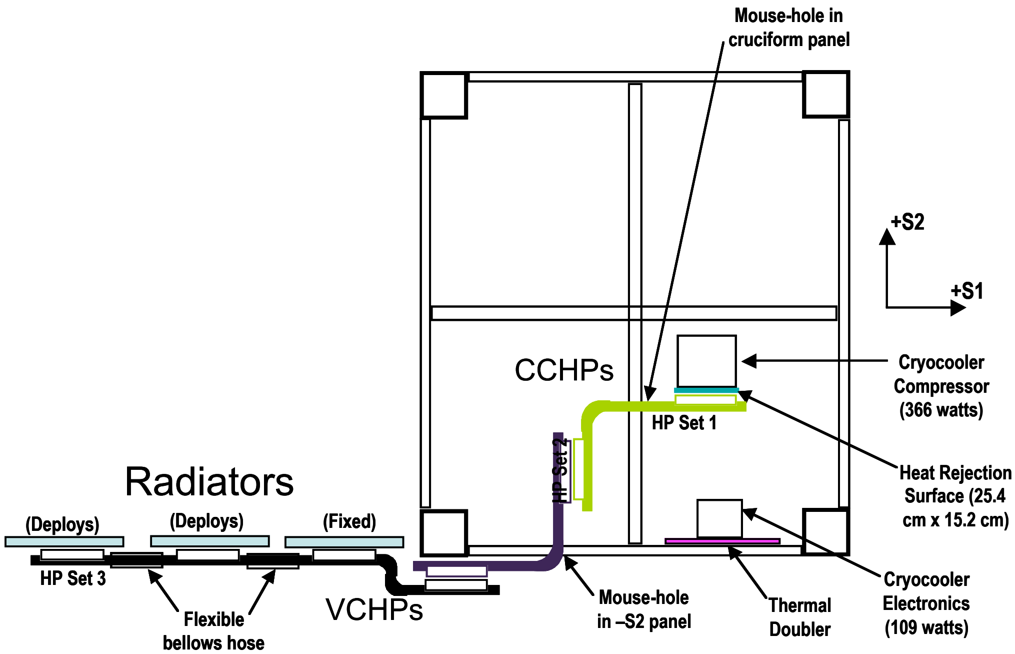


Figure VII-6: JWST Cryocooler Compressor Heat Rejection Concept

Sunshield/cooler demonstrator scale
Because of SAFIR's large size, there will be no opportunity to thermally test it at temperature in its final deployed flight configurations. JWST is managing this risk by performing a high fidelity thermal balance test on a test article approximately 50% of the size of the flight observatory. This test is designed to validate the overall passive cooling system approach and correlate the very complex thermal models that need to accurately predict the complex radiative interchange among the various observatory elements. The sub-scale high fidelity test envisioned for SAFIR could utilize the same large Helium shroud system at the JSC chamber A facility. The test would differ from JWST's in that it would be the best opportunity to also verify the mechanical cooler system operates as planned under realistic loading conditions. This test should occur early in SAFIR's development when the engineer cooler units are available. This test would ultimately validate SAFIR's overall thermal architecture approach and significantly reduce risk throughout the rest of SAFIR's development.

Cooler heat rejection system testbed
The second critical developmental test would be the cooler system heat rejection test bed test. This test would serve to verify at the engineering test unit level that the proposed heat rejection two-phase technology and radiator system works as modeled. Critical objectives of the test would be to measure and validate the temperature drops across the numerous interfaces from the cooler compressors to the radiators.

Spacecraft/cryocooler thermal balance test
The only thermal system verification test realizable at the flight unit level would be the spacecraft thermal balance test where the cryocoolers are exercised with simulated loads. This test could also occur in the JSC Chamber A facility, but without the telescope, instruments, and sunshield. Further studies of the test approach may show it feasible to include the entire observatory, minus the sunshield, for such a test. This test would be a true end to end system test of the flight observatory cryocooler system. JWST test studies have shown it unfeasible to include both the spacecraft bus and the telescope/instrument compliment in any system level cryo-test.